FULLY-ADAPTIVE SEATBELTS FOR FRONTAL COLLLISIONS

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Paper Number 05-0127

ABSTRACT

The goal of this paper was to demonstrate the potential for a fully adaptive restraint system to significantly reduce injuries. To accomplish this, a three-bodied model of a 50th percentile Anthropometric Test Dummy (ATD) in a 35 mph frontal collision was made using Lagrangian Dynamics. The model was verified against test data obtained from NHTSA. Viscoelastic and constant force seatbelt models were created, and the results were compared for a 1998 Chevy Malibu. The simulation accurately reproduced the shape and magnitude of pelvis, chest, and head accelerations. The constant force seatbelt reduced pelvis, chest, and head accelerations by 56%, 62%, and 63%, respectively. The peak lap belt force was reduced by 60%. Relative head rotation was reduced by 16 degrees. A simple control concept was explored and demonstrated the feasibility of an adaptive constant force restraint system. Such restraint systems can make large reductions to risk of injury by significantly reducing forces and accelerations on the occupant.

INTRODUCTION

In 2003, there were over 2.8 million people injured and 32000 killed in over 6.3 million motor vehicle accidents in the US. The restraint system is intended to reduce the risk of these injuries and deaths, but the seatbelt alone only reduces risk of injury by 45-50% for front seat occupants.[18] Air bags, pretensioners and load limiting devices have been introduced to remove slack and better couple the occupant to the vehicle during ride down, resulting in reduced seatbelt forces being exerted on the occupant. While these devices are beneficial, most are not adaptive to each crash and occupant.[17] Therefore it is believed that an adaptive seatbelt and restraint system, using sensor data collected before and during a crash, could potentially reduce injuries by tuning the restraint for each occupant, vehicle, and crash severity.[1, 12]

The primary goal of this work was to demonstrate the potential for an adaptive restraint system to reduce occupant injuries by showing that a constant force seatbelt can reduce forces and accelerations on an occupant. This was shown in the case of a frontal collision of a passenger car into a fixed-rigid barrier at 35 mph with no offset. It is assumed that an adaptive system can be designed and controlled to provide an optimal force level as determined prior to the start of the crash. There was no physical testing carried out to verify these results. Simple analyses were used to contribute to the work and concepts that are necessary for further development of this technology. The concepts developed here can be expanded to an entire adaptive system that would include the air bag. This work does not promote the elimination of air bags, but rather that an adaptive system offers many improvements over current seatbelt restraints. Controlling the seatbelt is preferred because it already contacts a restrained occupant at the beginning of the crash. Therefore, a dynamical analysis was carried out to determine to what extent seatbelt design affects injuries, as inferred from seatbelt forces and occupant accelerations. A simple control example is also shown which demonstrates the basic ideas formed here, and allows basic conclusions on adaptive restraints to be drawn.

BACKGROUND INFORMATION

There are many methods and approaches used in the literature to simulate occupants in a variety of crash scenarios. Most occupant models reflect the mass and geometry of a 50th percentile male ATD since it is used most frequently in crash tests.[9] It is necessary to note that even though an ATD is classified into a percentile, rarely is an actual occupant classified under the same percentile in all body characteristics. Happee[8] et al have noted that through the use of scaled crash-dummy models it is possible to simulate crash events for occupants with anthropometry not currently represented in available ATDs. The assumption of scalability can allow conclusions reached through simulation to be extended to occupant anthropometry not investigated.

It was found that two-dimensional models could adequately simulate restraint systems, and vehicle and occupant response without delving too deeply into the complexities that arise from three-dimensional analyses. This is especially true when computation capabilities are limited or large-scale simulations are unwarranted.[7, 22]

Many mathematical models of the human body emphasize the main body components[13], which are treated as an articulated assembly of rigid bodies defined to realistically represent the geometry and response of the occupant and vehicle.[22, 23]

Functional mathematical models of the seatbelt[13, 23] are preferred because they better model the viscoelastic nature of seatbelts, and they are less restrictive than mechanical spring-mass-damper models[23, 25].[3]

There are two methods to achieve a constant restraint force. The first method is to alter the force-deflection characteristics of the seatbelt such that the force remains constant while the belt elongates, resulting in a seatbelt having elastic-perfectly plastic load-elongation properties.[22] The second method to attain a constant restraint force is to physically control the seatbelt with an actuator so that the load remains constant. The actuator would quickly react in a crash to pretension the belt to some predetermined value, at which time would actively control how much webbing is released or collected to maintain that force. The constant force seatbelt considered here will assume the controlled constant force, although without concern to how it is attained or maintained.

Miller[15, 16] shows that variable load limiting would produce significant improvements in injury by tailoring to the needs of the occupant based on anthropometry. However, the results do not strongly emphasize the benefits of continuously variable load limiting. Here 'continuously' variable is used to draw a difference between systems with infinite settings and those systems with only two or three fixed levels[4]. Overall, a majority of the published work on constant force restraints relies heavily on repeated full-scale crash tests and focuses more on a discrete approach to occupant protection using existing technology.[1, 15] For this reason, this work focused on a simulation-based constant force restraint that is assumed to be infinitely variable and is provided by some adaptive and controllable system.

The most applicable work done in the area of adaptive restraint systems is by Hesseling. Hesseling[9, 10] uses an optimal control method to find a controllable restraint system to optimize the chest and head accelerations of a 50th percentile ATD. The important difference between work by Hesseling and that by Miller is that the seatbelt tension and air bag vent diameter are completely controllable, rather than fixed at some optimal level that is parametrically determined.

This paper addresses several conclusions and recommendations made by Hesseling. Hesseling asserts, "…a manageable model that describes the relevant aspects of the dummy, the restraint system, the vehicle and their interactions with an acceptable accuracy would be…useful."[9] In this work, a simplified model was created that can reproduce key aspects of the system, and it was used it to demonstrate the benefits of an adaptive constant force restraint. Control systems were not the focus of this work. However, some basic conclusions on the matter will be discussed.

The most applicable work done in the area of constant force restraints is done by Crandall.[5] Crandall uses optimization to find an optimal restraint force to minimize the Thoracic Injury Criteria. The optimal force is similar to the controlled constant force model discussed previously. Like Hesseling, Crandall's work shows that the optimal restraint force may not be constant, and requires an initial pulse that then reduces to lower values. The restraint force found by Crandall is close in shape to a constant force restraint; if used, results in a near optimal response of the chest acceleration. The goal of this work was not to derive an optimal solution, but rather focus on the established work that shows that a constant force restraint (CFR) offers drastic performance improvements in frontal collisions over currently available systems.[17]

Adaptive restraint systems will be closely tied to pre-crash detection.[12, 24, 27] A typical progression of a crash is depicted in Figure 1. With current technology, the occupant is not well restrained until the pretensioner tightens the belt roughly 15 ms into the crash. This time delay is due to a combination of effects from sensing the crash, to the pretensioner response time. In this example describing pre-crash technology, the pretensioning could begin at t=-15 ms, so that the belt is already taut and pretensioned as determined by the information collected by the sensors before crash initiation at *t*=0. The benefit of integrating adaptive restraint systems with pre-crash technology is twofold. The adaptive restraint can actively control the response of the occupant by removing slack and better coupling the occupant to the vehicle before the crash begins, and it also reduces the magnitude of the required restraint force.

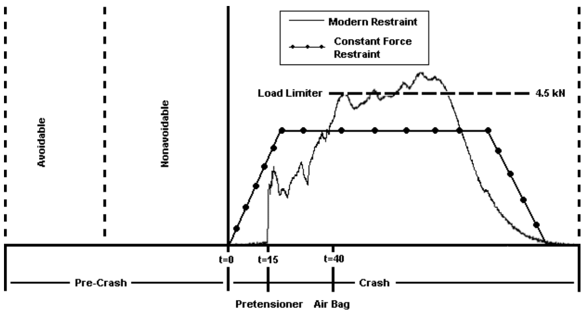

Figure 1: Crash event comparison of an adaptive restraint system with pre-crash sensors to current restraint systems.

There are a few load limiter designs on the market that can adapt to the crash environment, but do so only at discrete, predetermined levels.[4] Load limiters that can offer continuously variable levels of restraint have been developed, at least in theory, at some automotive companies. Takata[11] and Delphi Technologies, Inc[2] currently hold patents for load limiting devices that utilize magnetorheological (MR) fluid dampers to provide a continuously variable level of resistance. The variable resistance is typically obtained by allowing the fluid to flow through ports where electromagnets control the fluid's viscosity.

In 2003, TRW's Active Control Retractor became the first commercially available active seatbelt system. This system, utilizes pre-crash information from braking and stability control sensors to pretension the seatbelt with an electric motor. Takata also holds a patent for a variable pretensioning and load limiting system. Takata's adaptive system utilizes an electric motor for pretensioning and a MR-fluid load limiter, and together it could potentially provide the adaptive restraint necessary to fully realize the benefits of a constant force restraint. With the exception to those discussed above, it should be noted that a majority of this technology only appears in vague descriptions in the literature and patents. This author has no knowledge of physical systems existing, nor does there appear to be much testing or computer modeling of adaptive seatbelt restraint systems.

It is unclear at this point in time what form an adaptive restraint system will take when commercially available. With this in mind, the control for the adaptive CFR modeled in this paper was considered a 'black box' actuator. A model of how the adaptive control device responds can be added once it is available, and can be used to develop control laws. The 'black box' method also lends it to an open-ended design and simulation tool for restraint systems and controllers, without making any assumptions on the form of future technology. This simulation will be a useful tool to researchers to verify control strategies and develop alternative future restraint systems.

METHODS

The occupant was modeled with three rigid bodies and derived with Lagrangian Dynamics. The viscoelastic seatbelt was modeled as a system governed by a multivariable polynomial. The constant force seatbelt was modeled as a linear, piece-wise continuous, function of time. The vehicle was modeled as a deformable body governed by impact dynamics with a rigid barrier. The motion of the occupant and vehicle were found, but no interference between the two was included. A MATLAB program was written to simulate the system in a 35 mph frontal collision. This model was verified against real test data obtained from NHTSA.

Four primary assumptions were used in the model. It was assumed that the restraint forces act in only the direction of motion of the vehicle. This was done because of variance in seatbelt geometry between different vehicles. Also, assuming the forces only act in the horizontal directions reduced the complexity of the Equations of Motion (EOM), saving time in the derivation and solving of the equations. The occupant was modeled with rigid bodies, eliminating chest compression and torso bending. Friction was ignored since the coefficient of friction between body and seat will vary with each vehicle and model of ATD, giving conservative results.[7] All secondary collisions with air bag, dashboard, steering wheel, and seat interactions were ignored.[1] The model simulates the occupant-seatbelt interaction, and the adaptive restraint systems will be such that interior collisions do not occur, thus the need for modeling interior collisions is nonexistent. The locations of the dashboard, steering wheel, and air bag were tracked using the vehicle deceleration model and used as a reference when determining if a collision would occur.

Lagrangian Dynamics is a more favorable approach than Newtonian Dynamics for three main reasons. The first reason is that it provides a better understanding of the dynamics of the system because the system's kinetic and potential energies are used to derive the EOM. The second reason is that through the use of generalized coordinates, the number of equations that must be solved is reduced. The third reason is that it eliminates the need for including forces of constraint because they do no work on the system. The constraint forces include reactions forces from the seat and the joints of the body.

Thus the general approach to determining the EOM for the system is to formulate the Lagrangian L by deriving the kinetic energy T, potential energy U, and external forces Q in generalized coordinates q, where $L(\tilde{q},\dot{\tilde{q}},t)=T(\tilde{q},\dot{\tilde{q}},t)-U(\tilde{q},t)$ and $\tilde{Q}(\tilde{q},\dot{\tilde{q}},t)$.[19] The EOM can be determined with equation 1 and solved. Several iterations of one and two-bodied occupant models were used to arrive at the final three-bodied model used in this paper, shown in Figure 2, and Tables 1-3. Note that in Table 1 the mass of each model component is found by the product of the mass of the occupant by the percent mass of that component. Also note, that the total mass of the modeled body is not the total mass of the occupant, since it is assumed that a portion of the mass from the arms and lower legs is ignorable.[22]

$$\frac{d}{dt}\left(\frac{\partial L}{\partial \dot{q}_i}\right)-\left(\frac{\partial L}{\partial q_i}\right)=Q \qquad (1).$$

Table 1:

Mass and inertial values for a three-bodied occupant model, see Figure 2

Mass [N]	% Masses			Radii of Gyration k [m]	
Total	Pelvis	Torso	Head	Torso	Head
766.43	.2983	.5148	.07777	.2840	.1464

Table 2:

Size dimensions [m] for a three-bodied occupant model

Pelvis	Chest		Head	
Length	Height	Width	Height	Width
.59	.508	.254	.254	.2032

Table 3:

Joint Parameters for a three-bodied occupant model

	Hip	Neck		
		Low	ϕ_{limit} [Deg]	High
Spring [N m]	100	7	±30	70
Damper [N m s]	10	10	NA	

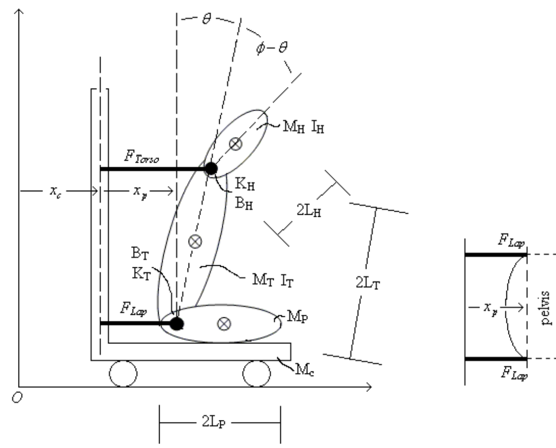

Figure 2: Three-bodied occupant model restrained by a torso and lap belt, dimensioned as shown. Figure on right shows geometry of lap belt on pelvis.

The general approach taken by these authors is as given, and more information can be found by referring to work by Paulitz.[20, 21] First a dynamic model of a 50th percentile ATD approximation was done using the model above with a function-based mathematical seatbelt model. This model was piecewise continuous in force-displacement space. While the belt is elongating, the force-displacement relation is given by a multivariable polynomial cubic in elongation and linear in rate of elongation. While the belt is relaxing the relation is given by a quadratic in elongation only. This model has been shown to closely match the behavior seen in testing.[13, 14] The coefficients for the elongating portion were determined by parametrically altering the values until good correlation was seen between the model seatbelt force and body accelerations and the data obtained from NHTSA. The coefficients for the relaxing portion were determined by assumptions of continuity and some inherent belt properties. This resulted in a functional model of the viscoelastic seatbelt that is believed to be accurate, at least in relation to the assumptions and cases studied.

These results were then compared to those when the viscoelastic seatbelt is replaced by a constant force seatbelt. This was modeled as a constant with a linear ramp done over a period of 10 ms, although any non-zero time can be used. The magnitude of the CFR is determined by parametrically varying the values until the occupant excursion is maximized while interior collisions are prevented. The CFR makes no assumptions about how the force is created or maintained, so the force can be prescribed simply as a function of time rather than finding some relation in the state variables. This model was used to illustrate the possible benefits of a truly constant force restraint that could be provided by some kind of controllable and adaptive system.

The last part of the study involved combining the two models. The viscoelastic restraint model (as earlier determined) was used but is attached to some actuator rather than connected directly to the vehicle. The response of the actuator is then determined such that the restraint force exerted on the occupant is that of the CFR (as earlier determined). This provides insight into the behavior and control issues of such a model, as well some physical characteristics that may need to be considered of the seatbelt and actuator systems.

Results

The simulation results showed that the collision model with a viscoelastic seatbelt is accurate and correctly simulates the system dynamics. The results were found by comparing the simulation to the available test data from similar crash tests. The results shown are for the model verified against a test of a 1998 Chevy Malibu. The vehicle deceleration model was adjusted to the test data and values of k = 1.2, t_f = 105 ms, and V_0 = 15.728 m s^{-1} were found. The acceleration profile of the vehicle is shown in Figure 5; note the data plotted does not contain every data point from the test. Briefly, the vehicle deceleration model is a parabolic equation whose coefficients are determined by the placement of the zeros, $t=0,t_f$, and the total change in velocity kV_0 where k is assumed to be between 1 and 2.[20, 21] The simulation results for the 1998 Chevy Malibu were obtained with the seatbelt properties given in Tables 4-5 and Figure 4.

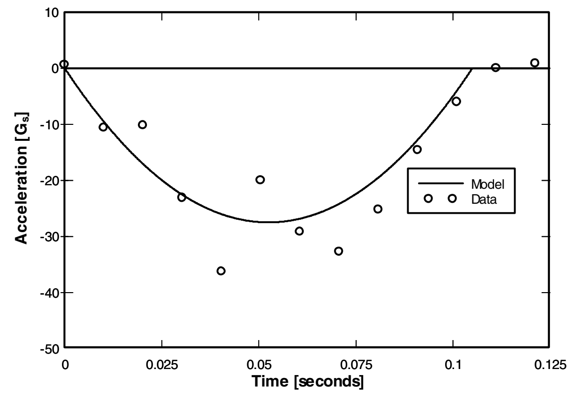

Figure 3: Vehicle A(t) as compared to accelerometer data of a 1998 Chevy Malibu (O) in a 35 mph frontal crash.

Table 4:

Viscoelastic seatbelt coefficients for a 1998 Chevy Malibu

	Cubic [kN m^{-3}]	Quadratic [kN m^{-2}]	Linear [N m^{-1}]	Damping [N s m^{-1}]
Lap	300	200	30	600
Torso	200	115	20	600

Table 5:

Constant force seatbelt parameters for a 1998 Chevy Malibu

	Force F [N]	Tension Time T_t [ms]
Lap	3800	11
Torso	4200	10

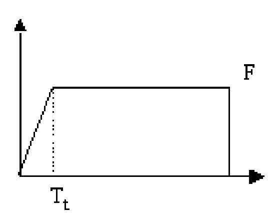

Figure 4: CFR profile, as determined by magnitude F and rise time T_t.

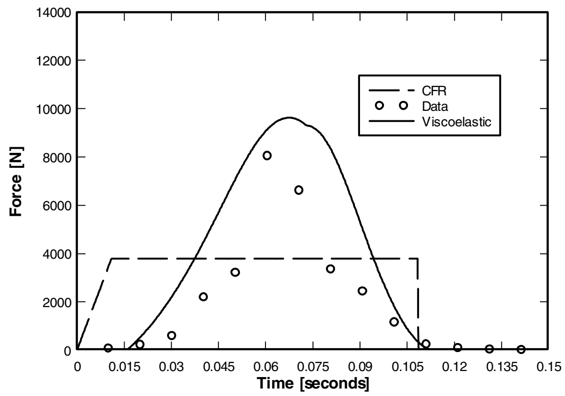

Figure 5: Lap belt F(t) comparisons between viscoelastic and constant force seatbelt models, as compared to data of a 1998 Chevy Malibu (O).

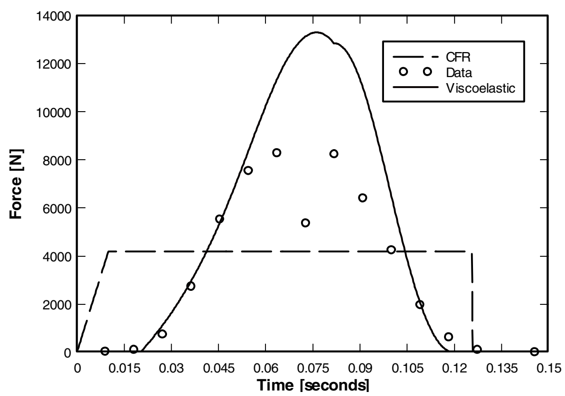

Figure 6: Torso belt F(t) comparisons between viscoelastic and constant force seatbelt models, as compared to data of a 1998 Chevy Malibu (O).

The seatbelt force and body acceleration results for both restraint models are shown in Figures 5-9. The dashed line denotes the results for the constant force restraint (CFR), and the solid line denotes the results for the viscoelastic restraint. The open circles denote the corresponding measured data for the crash test. In general, the results for the viscoelastic model of the lap belt are conservative, where higher belt forces and accelerations are usually predicted. It is clear that the constant force seatbelt can result in lower restraint forces exerted on the occupant, and drastic reductions in pelvis, chest, and head accelerations. A more thorough discussion is given in [20, 21].

Some additional comments, the peak value of the simulated viscoelastic torso belt force in Figure 6 is highly conservative. The shape is similar during increasing load, until 50 ms into the crash when it is presumed the stitch-tearing load limiting is occurring. In this vehicle, load limiting is achieved through tearing of stitches in the seatbelt. This could be because the restraint model stretches and yields in a continuous fashion, while in real-life this occurs discretely. The continuous model was used for simplicity and because the conservative belt forces did not appear to result in large deviances in the accelerations, possibly because while the simulated torso belt force is over estimated, it is accounting for restraint that would be offered by the air bag.

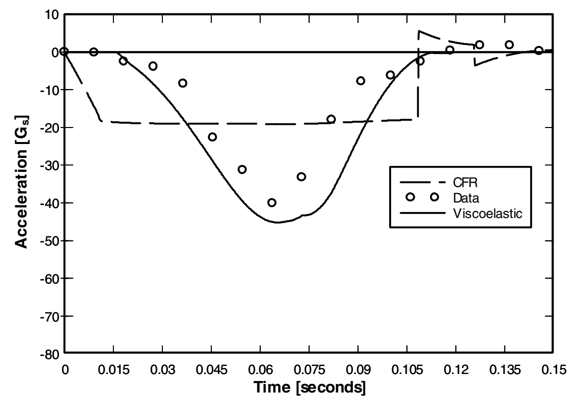

Figure 7: Pelvis A(t) comparisons between viscoelastic and constant force seatbelt models, as compared to data of a 1998 Chevy Malibu (O).

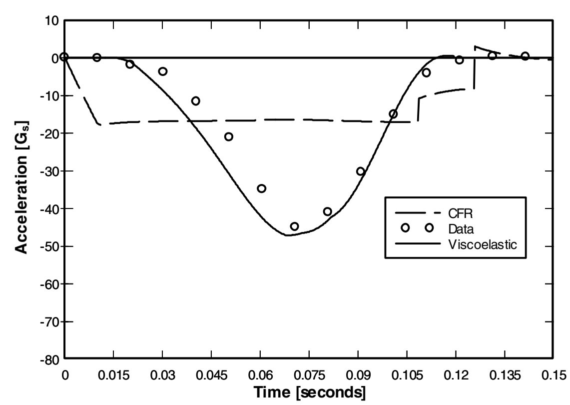

Figure 8: Chest A(t) comparisons between viscoelastic and constant force seatbelt models, as compared to data of a 1998 Chevy Malibu (O).

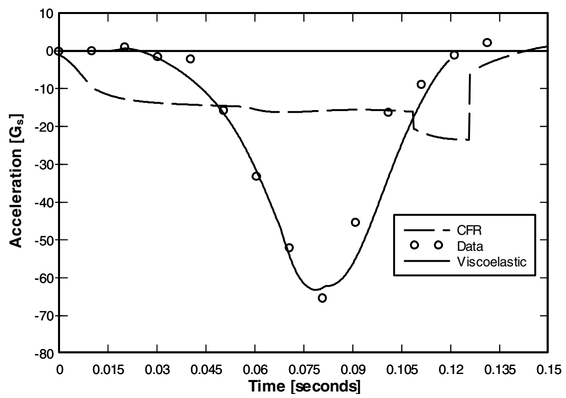

Figure 9: Head A(t) comparisons between viscoelastic and constant force seatbelt models, as compared to data of a 1998 Chevy Malibu (O).

The only negative aspects found of the CFR results are the discontinuities in acceleration, as seen in Figures 7-9. The largest discontinuity seen is roughly 24 G in magnitude, but is not critical because the pelvis is less prone to injury due to large changes in acceleration than the head and neck. Although the sudden change in acceleration subjected to the head and neck may prove injurious. Mathematically, the discontinuities in the accelerations result directly from the discontinuities in the constant force profiles for the torso and lap belts. Piecewise continuity in the constant force profile will remove the discontinuities and yield smoother results. This could be accomplished by giving the $F_{CFR}(t)$ a trapezoidal shape rather than a step shape at the end time. For this reason, the affects of the discontinuities will be for the most part ignored since later simulations could be corrected to reduce their effect.

Perhaps one of the greatest benefits of CFR systems is the possible reduction in head injuries. The general response of the head acceleration for both restraint models differs from those of the pelvis and chest because it is free to respond and is not directly coupled to the vehicle through the restraint. The CFR results in a 62.8 % reduction of head acceleration, even when considering the spike of 23 G. This large reduction could greatly reduce the risk of head injury. The HIC value was not calculated, but it is clear in comparing the shapes of the head accelerations resulting from two seatbelt models that there is a large difference in the area under each curve, inferring large HIC reductions.

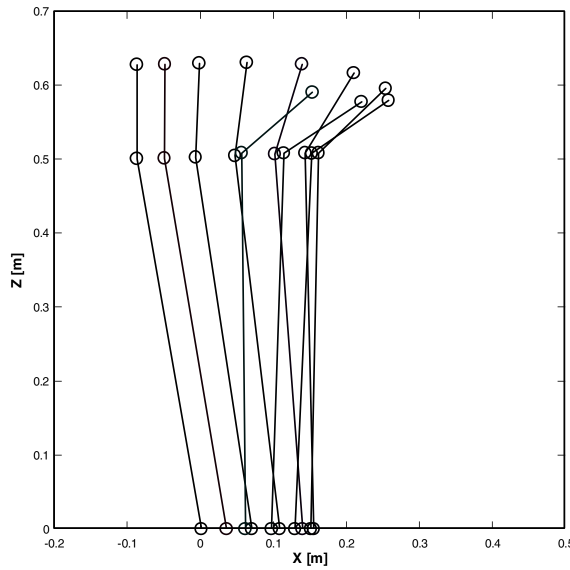

Figure 10: Relative motion of pelvis, torso and head within 1998 Chevy Malibu using a viscoelastic seatbelt model.

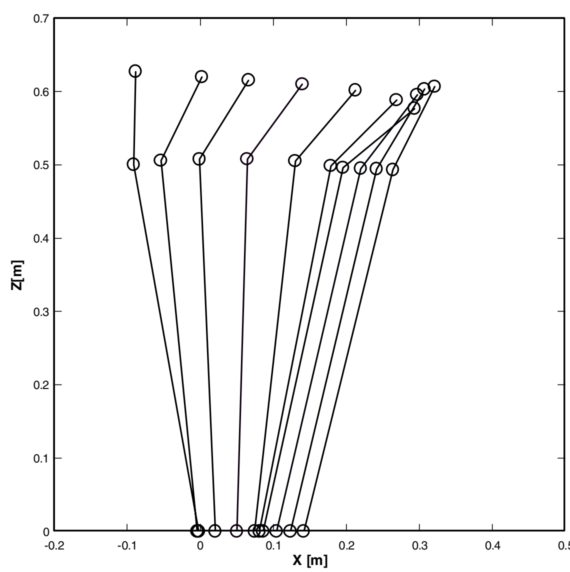

Figure 11: Relative motion of pelvis, torso and head within 1998 Chevy Malibu using a constant force seatbelt model.

The physical motion of the occupant with-respect-to to the Malibu is shown in Figures 10-11. The lines define the centerlines of the torso and head. The markers define the motion of the hip, shoulder, and head/neck cg. Figure 10 illustrates the motion under the viscoelastic seatbelt model, and seems to match with the observed motion during the collision. The body typically translates and rotates forward to a near vertical position. The head rotates forward and the largest relative rotation is seen after the maximum chest excursion. The curve the head Cg follows in space is similar in shape to that shown in the literature [6, 9]. Figure 11 illustrates the motion of the body under the CFR model, where occupant excursion is increased substantially. This result was anticipated as it was assumed that the constant force restraints would increase excursion, making use of more of the available space in the compartment. The relative motion of the head is improved as well, with a dip in the motion of the head as the occupant nears maximum excursion, and is likely caused by the discontinuity in the constant force seatbelt model.

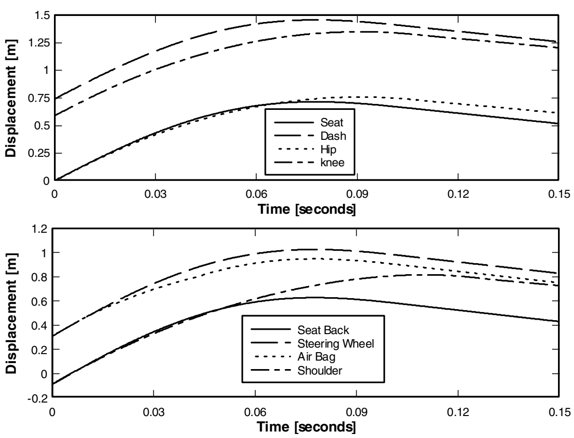

Figure 12: Global motion of pelvis and torso with 1998 Chevy Malibu using a viscoelastic seatbelt model. Top figure is thigh motion with seat and dashboard; bottom figure is shoulder motion with seat, steering wheel, and air bag.

Figure 12 illustrates the global motion of the body. The lines denoting the motion of the occupant denote motion of the centerlines, and do not account for chest depth. One benefit of the CFR model is that rebound of the occupant after maximum excursion is limited, as shown in Figure 12 where the knee and chest approach but do not cross the lines denoting the dashboard and air bag. The values for the CFR were found such that internal collisions were prevented and the rebound rates of the vehicle and occupant matched on a global level. Large rebound rates could result in neck injuries, and suggests that more than required restraint force was applied and could therefore be reduced.

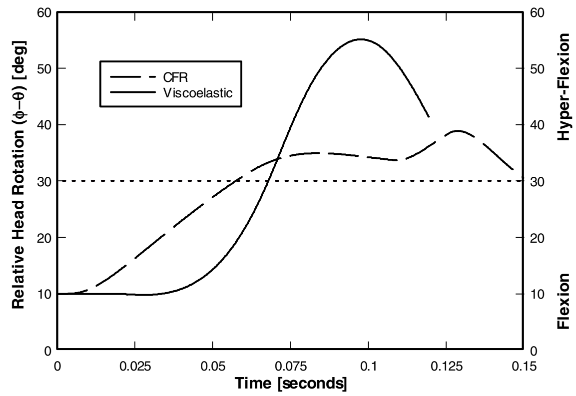

Figure 13: Relative head rotation $\phi(t)-\theta(t)$ comparisons between viscoelastic and constant force seatbelt models of a 1998 Chevy Malibu.

The relative rotation of the head about the torso is given in Figure 13 for both restraint models. The maximum rotation for the viscoelastic restraint model is 55.14 degrees, and for the CFR model it is 38.9 degrees, a 29.5 % reduction. The shape and magnitude are similar to data published of expected head rotations for the human body [6]. One conclusive benefit of the CFR system is that it reduces peak relative head rotation; it also broadens the amount of time the rotation occurs. In the viscoelastic restraint model, the head remains fixed relative to the torso until about 40 ms at which time the head begins to rotate forward at a high rate. For the CFR model the head rotation begins to increase noticeably at about 10 ms, at a much gradual rate. The large reduction in relative rotation into the region of hyper-flexion should greatly reduce injury, as shown on the right hand side of Figure 13.

“Black Box” Controller

Having established a viscoelastic and a constant force seatbelt model, it was then possible to combine them to create a basic control concept for an adaptive constant force restraint. The restraint control was not the focus of this work, rather the simulation of the restraint, so a large amount of effort was not put forth into creating a full-scale feedback-control system to realize a truly adaptive seatbelt.

The general concept is that it is possible to apply a predetermined force to the occupant, without concern to how it was achieved. With this approach, it is possible to obtain some general guidelines of what physical characteristics such a system should have and what kind of response would be expected from the control system. The basic control was found by combining the constant force profile to the viscoelastic seatbelt model that is a function of belt elongation. The device providing the control will be coupled to the body through the seatbelt. So it is believable that an adaptive control scheme would include both models. The controller would act like a pretensioner that could pull and release the belt such that the response to the viscoelastic restraint in a collision is transformed into the response seen under a CFR.

In theory, an adaptive restraint system might look like that shown in Figure 14. The viscoelastic belt models are rewritten so that rather then being only functions of occupant displacement with respect to the vehicle, they are functions of belt elongation *d*. Here *d=x-y* where *x* is the occupant motion with respect to the seat, and *y* is the motion provided by the actuator which is considered controllable; no constraints were placed on the magnitude of y or $\dot{y}$ at this time. To determine the *y(t)* output for the controller, the constant force seatbelt model is equated to the viscoelastic seatbelt model with the coefficients determined previously, as shown by equation 2. Equation 2 can be included in to the CFR simulation, and *y(t)* can be found where $F_{CFR}(t)$ and *x(t)* are determined through simulation as discussed previously.

$$F_{CFR}(t) = F_{VISCO}(x - y) \qquad (2).$$

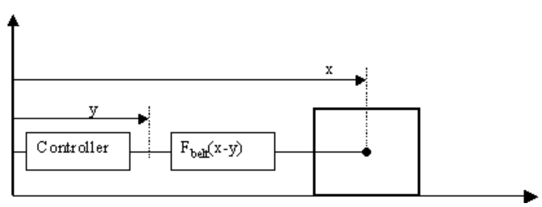

Figure 14: Basic adaptive seatbelt controller schematic. ***X*** **denotes the displacement of the occupant;** ***y*** **denotes the displacement done by the controller such that** $\mathbf{F_{belt}(x\text{-}y)}$ **is constant.**

Using this method, the response of the controller for an adaptive constant force restraint was found. The response for both belts is shown in Figure 15 and 16. Here, the response of the control will be referred to as the Active Force Response, where the pretensioning device actively controls *y(t)* to maintain a constant force while the body is moving. This device and the seatbelt system as whole will be referred to as an Adaptive Restraint System, where some *a priori* decision is made as to the magnitude of the force required, and the AFR responds accordingly to provide that force based on simulation. Later, feedback would be included that would allow the AFR to respond to changes that occur during the crash. This could include a secondary collision in a multi-vehicle crash, or an over- or under-prediction of occupant motion. In any case the AFR would respond to increase the load or decrease the load to the necessary value to prevent collisions and reduce injury. Such a system should replace current pretensioning and load limiting systems.

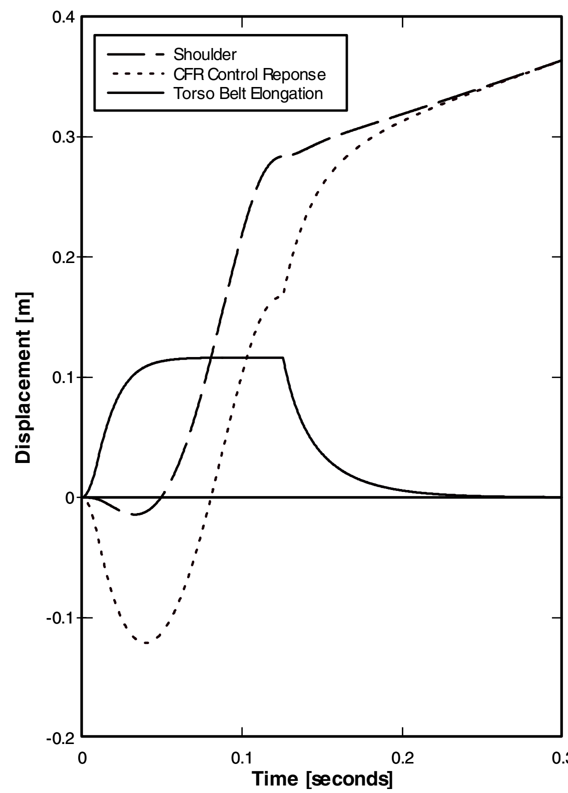

Figure 15: Active Force Response of torso belt for 1998 Chevy Malibu to provide a constant force from a viscoelastic seatbelt model.

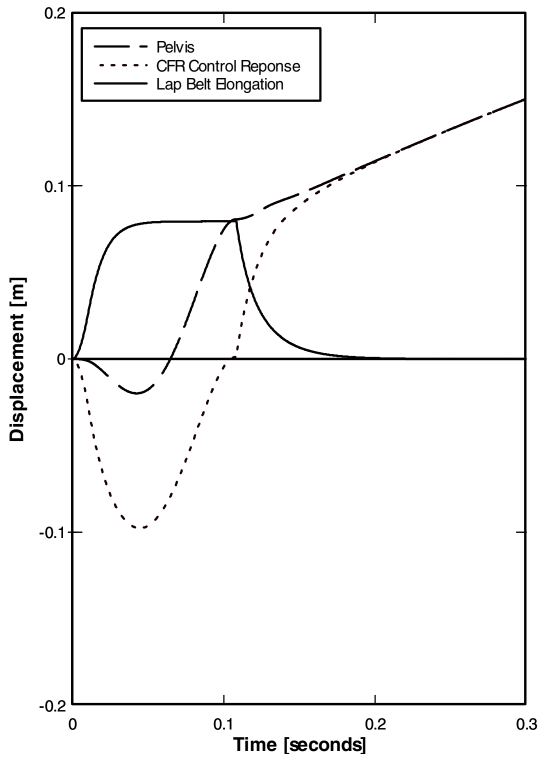

Figure 16: Active Force Response of lap belt for 1998 Chevy Malibu to provide a constant force from a viscoelastic seatbelt model.

The response for the torso belt is shown in Figure 15, and the response for the lap belt is shown in Figure 16. The solid lines denote the belt elongation. It is worth noting that these curves match those expected for the creep and recovery of a viscoelastic material[3]. The portion with negative concavity denotes the loading of the material, and the portion with positive concavity denotes the response once the load has been removed. The extension phase also matches expected behavior of a Voigt-Kelvin material model to a unit force.[3] This suggests that although the mechanical Kelvin/Voigt model was not used for the restraint system, the polynomial function chosen does respond similarly.

The dashed lines denote the motion of the body, where in the torso plot it is the motion of the shoulder, and in the lap plot it is the motion of the pelvis. As the device begins to pull the belt out away from the body to increase the load, the body does move backwards some amount. While this amount is small, it suggests that at least a simple model for a seat back should be included at some future point.

The dotted lines denote the response *y(t)* of the AFR. In general, the shape tends to follow that of the motion of the occupant, although with larger magnitudes. The device would have to be capable of retracting about 5 inches on the torso belt and about 4 inches on the lap belt. An important note here is that no slack was considered for these models, so the retraction capabilities would be this value plus some estimate for a slack value based on occupant position and size. These models also require an elongation of the torso belt on the order of 4.5-5 inches and an elongation of the lap belt on the order of 3 inches. However, this is for the 50th percentile person, so for a smaller occupant less would be necessary, and the bounds for this would have to be established by the largest expected occupant, 95th or higher percentile.

This model assumed that the seatbelt itself is performing all the restraint, and may be limited by the performance of the webbing in maximum allowable elongation. The allowable elongation will depend on the length of the seatbelt itself, which was not considered. If good estimates of belt length and size were available along with the test data used to obtain this model, then a better idea of the limitations for the load control could be found. This may be found to be limited on either the amount of webbing the retractor can actually reel in or the amount of strain the belt can withstand. Although, in comparing the amounts of elongation between the viscoelastic and adaptive models, this does not appear to be an issue at present. If the limiting factor is found to be a material property of the belt, it may be possible that realizing a restraint of this design could require new and advanced polymers for use in seatbelts specifically tailored for use in adaptive seatbelts.

Another solution could be the use of the air bag to provide supplemental restraint. If the seatbelt ‘knew’ how much restraint the air bag would offer for a particular occupant and crash, it could tailor the seatbelt force with this in mind such that together they offer the restraint necessary for preventing injury rather than relying solely on the seatbelt itself. These cases will all have to be accounted for in the design of the controller, since there will be certain bounds based on physical and mechanical limitations of the system.

Conclusions

The simulation considering a viscoelastic restraint can reproduce test data from certain vehicles with acceptable accuracy. Good correlation was seen between the pelvis, chest, and head accelerations and satisfactory correlation was seen between the lap and torso belt forces. Drastic reductions in seatbelt force and occupant accelerations were achieved through the use of a controlled constant restraint force profile. This restraint was defined to closely relate to modern load limiting and pretensioning technology but do so in an improved fashion. These improvements warrant the further investigation of controlled and adaptive constant force seatbelts.

The adaptive restraint system outlined here controls the belt elongation to maintain the restraint force at a constant level as the occupant moves through the vehicle. Such a system would adapt to the crash environment by making control decisions on restraint force based upon occupant size, weight, and location, as well as crash severity. This forms the basic theory for an adaptive restraint system. An adaptive restraint system would consist of a controllable seatbelt and air bag that are in constant communication with one-another and sensor data to make control decisions that will drastically reduce occupant injury. This work has shown that an adaptive seatbelt will provide sufficient restraint and could greatly reduce risk of injury, especially HIC, in the cases studied. These systems suggest the potential for great benefits over conventional and constant force restraints achieved through non-adaptive and mechanical load limiting. It also has been shown that a means to control the seatbelt force is attainable, and a basic control strategy and concept has been proposed. While this is shown in the case of a mid-sized male occupant, it is believed that these benefits will apply to other occupant types. This will hold especially for those that are more susceptible to injury from high belt forces and occupant accelerations, such as children, women[26], and the elderly.

Recommendations

For larger occupants and in high severity crashes it is unlikely that the seatbelt alone will be able to protect the occupant from injuries. For these cases the air bag will still play an important role in injury prevention and reduction, so to extend the analysis of adaptive and constant force seatbelts to higher crash severities, it will be necessary to incorporate a model of the air bag, at least to some degree. Future analysis should also include the air bag to determine the possibility of timing the air bag inflation to provide additional head restraint later in the crash and help reduce the peak acceleration experienced by the head, and also the development of adaptive restraint systems that would include active seatbelts and air bags.

This work only considered frontal impacts of 35 mph, and it would be valuable to see the results for offset frontal, rear-end, and side-impact crashes using the restraint system proposed here. In these cases, it is not expected that the CFR will have as drastic improvements on injury, however no modeling of these cases was done here nor does there appear to be much done the literature in regards to constant force restraints in non-frontal collisions. Creating individual simulations of these cases could prove useful as well in determining improved restraint systems since it may be true that the best force with which to restrain an occupant in each crash orientation, i.e. frontal, rear, side, etc. may be different. However one physical device may be capable of creating the necessary restraint force. For a frontal collision, the adaptive restraint system would apply a constant force, but for a rear- or side-impact it could apply the necessary restraint to greatly reduce injury, as determined through simulations of these other cases.

With the purpose and goal of the simulations and models used and created here in mind, it is the authors' opinion that it is important that the models remain as simple as possible to be of most use. The recommendations pertain to the assumptions used to create these simplistic models. The direct influence of the assumptions made here should be better understood to ensure the soundness and robustness of the model as it exists and to find simple additions to the simulation that could improve its accuracy and usefulness. Once a continuously adaptive restraint system has been created and made available, it is also necessary to perform physical testing to verify these models. In the case that the test data does not correlate well to the predicted response, suitable corrections should be made while attempting to preserve the simplicity that is desired for controller design and feedback.

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